

IceCube: Neutrino Messages from GRBs

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Abstract. The mystery of where and how Nature accelerates the cosmic rays is still unresolved a century after their discovery. Gamma ray bursts (GRBs) have been proposed as one of the more plausible sources of extragalactic cosmic rays. A positive observation of neutrinos in coincidence with a GRB would identify these objects as sources of the highest-energy cosmic rays and provide invaluable information about the processes occurring inside these phenomena. Calculations show that a kilometer-scale neutrino telescope is necessary for this task. The idea of such a detector is now becoming reality as IceCube at the South Pole nears completion. The contribution reviews the status of the construction and operation of IceCube and summarizes the results from searches for neutrinos from GRBs and similar phenomena with IceCube and its predecessor, AMANDA. At the end, an outline of future plans and perspectives for IceCube is given.

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INTRODUCTION

Gamma-ray bursts (GRBs) are among the most violent events in the universe and among the few plausible candidates for sources of the ultra-high energy cosmic rays. So-called long-duration GRBs ($\gtrsim 2$ s) are thought to originate from the collapse of a massive star into a black hole [1], whereas short-duration GRBs ($\lesssim 2$ s) are believed to be the result of the merger of two compact objects (e.g., neutron stars) into a black hole [2]. Though quite different in nature both scenarios are consistent with the currently leading model for GRBs, the fireball model [3], with the energy source being the rapid accretion of a large mass onto the newly formed black hole. In this model, a highly relativistic outflow (fireball) dissipates its energy via synchrotron or inverse Compton radiation of electrons accelerated in internal shock fronts. This radiation in the keV–MeV range is observed as the gamma-ray signal. In case of long GRBs the energy in gamma rays is typically of $\mathcal{O}(10^{51}–10^{54} \text{ erg} \times \Omega/4\pi)$ where Ω is the opening angle for the gamma-ray emission. Short GRBs are observed to release about a factor 100 less energy.

In addition to electrons, protons are thought to be accelerated via the Fermi mechanism, resulting in an E^{-2} power law spectrum with energies up to 10^{20} eV [4, 5]. Protons of $\mathcal{O}(10^{15}$ eV) interact with the keV–MeV photons forming a Δ^+ resonance which decays into pions [6]. In the decay of the charged pions, neutrinos of energy $\mathcal{O}(10^{14}$ eV) are produced with the approximate ratios $(\nu_e:\nu_\mu:\nu_\tau) = (1:2:0)^2$, changing to about (1:1:1)

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² Here and throughout the rest of the paper ν denotes both neutrinos and antineutrinos.

at Earth due to oscillations [7]. First calculations of this prompt neutrino flux [6, 8] used average GRB parameters and the GRB rate measured by BATSE to determine an all-sky neutrino flux from the GRB population.

In a similar way, so-called precursor neutrinos can be generated when the expanding fireball is still inside the progenitor star [9]. In this case, the accelerated protons interact with matter of the progenitor star or synchrotron photons. However, due to the large optical depth the synchrotron photons cannot escape the fireball and, hence, no gamma-ray signal is observed.

THE ICECUBE NEUTRINO OBSERVATORY

IceCube [10], the successor of the AMANDA-II experiment and the first next-generation neutrino telescope, is currently being installed in the deep ice at the geographic South Pole. Its final configuration will instrument a volume of about 1 km^3 of clear ice in depths between 1450 m and 2450 m. Neutrinos are reconstructed by detecting the Cherenkov light from charged secondary particles, which are produced in interactions of the neutrinos with the nuclei in the ice or the bedrock below. The optical sensors, known as Digital Optical Modules (DOMs), consist of a 25 cm Hamamatsu photomultiplier tube (PMT) housed in a pressure-resistant glass sphere and associated electronics [11]. They are mounted on vertical strings where each string carries 60 DOMs. The final detector will contain 86 such strings spaced horizontally at approximately 125 m intervals³. Physics data taking with IceCube started in 2006 with 9 strings installed. Currently, 79 strings are deployed. The completion of the detector construction is planned for the year 2011.

SEARCHES FOR NEUTRINO EMISSION FROM GRBS

Detection channels

Charged secondary particles generated in neutrino interactions produce Cherenkov light patterns in the detector that can be separated into two classes (*channels*).

In case of an incoming muon neutrino which interacts via a charged current reaction, the so-called *muon channel*, the resulting outgoing muon leaves a track-like pattern of PMT signals in the detector. As the muon can travel up to several kilometer in water or rock the interaction can happen far away from the detector. Due to the long lever arm that is associated with the track-like pattern of PMT signals, this channel provides the best angular resolution for the direction reconstruction of the neutrino. For energies above 1 TeV it is better than 1° . At energies below $\sim 10 \text{ TeV}$ it is dominated by the unknown angle between the reconstructed muon and the original neutrino. The angular resolution improves with energy and at energies above $\sim 10 \text{ TeV}$ it is dominated by the precision

³ Six of these strings will make up a dense subarray in the clearest ice known as Deep Core, extending the sensitivity of IceCube at lower energies.

of the direction reconstruction of the muon. The energy resolution in this channel is rather poor ($\Delta \log E_\mu \approx 0.3$ [12]) as only part of the muon's energy is deposited inside the sensitive detector volume. In addition, an unknown amount of energy is transferred into the shower at the neutrino interaction vertex.

The so-called *cascade channel* consists of neutrino interactions which happen inside or near the detector and do not produce a high-energy muon. It is characterized by the Cherenkov light emitted from charged particles in the generated shower, which, within the position resolution of the detector, is point-like. Due to the short scattering length in ice, the angular profile of the light is isotropic after a few ten meters. As a consequence, the directional information is almost completely lost and the angular resolution for the neutrino direction is of the order of 30° . On the other hand, showers deposit all of their energy near the interaction vertex allowing for a better energy reconstruction than in the case of muons. In particular, in charged current electron neutrino interactions, all of the neutrino's energy is transferred into showers, allowing for an improved neutrino energy reconstruction. In contrast to the muon channel to which only muon neutrinos in charged current reactions contribute, the cascade channel is sensitive to all neutrino flavors.

Searches for neutrinos from GRBs are performed in both channels, where the main channel is the muon channel due to its superior angular resolution.

Analysis methods

Searches for neutrinos from GRBs are performed with and without the usage of information from other detectors, mostly satellites (e.g., Swift, Fermi), which trigger on the prompt gamma-ray emission of GRBs. In this so-called *triggered searches*, the knowledge of the direction and time of the emission allows for a significant reduction of background without loss of signal. This leads to an increase in sensitivity to a level where a single detected neutrino from a GRB can be significant at the 5σ level. Analyses are performed by estimating the expected background during the GRB emission from off-time data thereby avoiding uncertainties in the detector simulation for the calculation of the significance of a potential signal.

On the other hand, triggered searches rely on the detection of GRBs by satellites and hence miss all GRBs that are not seen because either they are not in the field of view of satellites or because the GRBs do not emit gamma rays. An example for the latter is the potentially large class of choked GRBs where the jet is not powerful enough to reach the surface of the progenitor star. In these cases, like in the precursor phase, neutrinos and gamma rays are emitted but only neutrinos can escape the dense source. Hence, the only detectors that can observe these GRBs are neutrino telescopes. In order to find a signal from these sources in the IceCube data, so-called *rolling searches* are performed. In these analyses, a time window with a width fitting the expected neutrino emission duration (typically between 1 s and 100 s) is moved over the detected events comparing the observed number of events with those expected for pure background. Though these searches are sensitive to all GRBs with neutrino emission, they are less sensitive for known GRBs due to the large trial factor resulting from the sliding window.

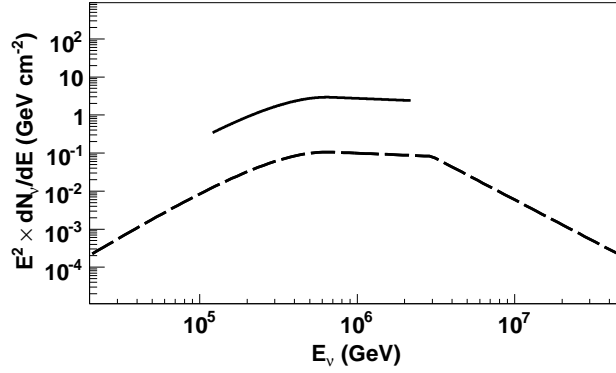


FIGURE 1. Calculated neutrino spectrum for GRB 080319B ($\Gamma = 300$; dashed line) and 90% CL upper limit from the analysis of IceCube data taken with 9 strings (solid line). Taken from [13].

Detection of Individual GRBs

According to current calculations, the expected number of detected events from an average GRB is rather low even in a km^3 -size neutrino telescope like IceCube (for an average Waxman-Bahcall burst it is of the order of 0.1 events). However, as discussed in [14] the burst parameters vary significantly from burst to burst leading to a large variation in the expected number of detected events. Thus, the individual analysis of data from exceptionally bright GRBs is highly interesting.

Such an analysis was previously performed with data from the AMANDA-II detector [15] with negative results. During IceCube operations, the so-called “naked-eye” GRB 080319B occurred which was the optically brightest GRB ever recorded. At that time, IceCube was running in a 9-string configuration. Calculations yielded that the expected number of detected events for a jet bulk Lorentz factor of 300 would be about 0.1 [13]. The analysis of the data [13] showed no significant excess above the background leading to the 90% CL upper limit on the neutrino flux shown in Fig. 1.

For the 10 times larger completed IceCube neutrino telescope, similar bright GRBs are expected to yield of the order of 1 event in the detector. Hence, the analysis of individual bright GRBs remains interesting.

Stacked GRB Searches

As the mean number of expected neutrinos from individual GRBs is usually small, stacking the events from the directions of several GRBs enhances the chances for a discovery. The disadvantage is that a potential signal cannot by implication be identified with a neutrino flux from a specific GRB.

So far, the most sensitive analysis with such an approach has been performed with data taken with IceCube in its 40-string configuration in 2008/09. Figure 2 shows the calculated neutrino spectra for 117 bursts (mainly detected by Swift and Fermi) that occurred during data taking. Differences to the flux from an average Waxman-Bahcall burst, which is also shown, are clearly visible. They are due to the fact that the average

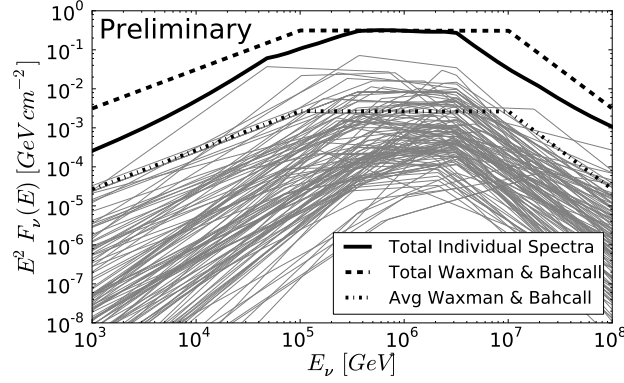


FIGURE 2. Calculated neutrino spectra for 117 bursts for which data has been recorded with the IceCube 40-string configuration (thin lines). Also shown is the sum of the 117 individual spectra (thick solid line), the flux from an average Waxman-Bahcall burst (dash-dotted line) and the sum of 117 average Waxman-Bahcall bursts (dashed line).

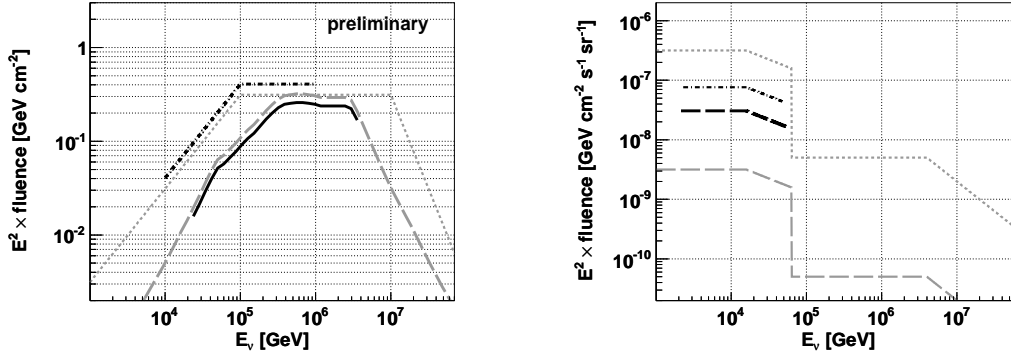


FIGURE 3. Left: Calculated total prompt neutrino spectrum from 117 bursts during the operation of IceCube with 40 strings (light solid line) and 90% CL upper limit (dark dashed line). In addition, the flux and 90% CL upper limit from the analysis of 416 bursts with the AMANDA-II detector (dash-dotted dark and light dotted line; scaled to 117 bursts) [16] is displayed. Right: Flux of precursor neutrinos according to [9] (light dashed line) and the flux scaled by a factor 100 (light dotted line) which assumes that all type II SNe exhibit choked jets. The dark lines represent the 90% upper limits from an analysis of IceCube 22-string data [17] (dark dashed line) and a rolling search in the cascade channel with AMANDA-II data [18] (dark dash-dotted line).

parameters of the GRBs in the BATSE sample used by Waxman and Bahcall for their calculations [6] differ from those in the Swift/Fermi sample (see [17] on how individual spectra are calculated). The analysis of the data yielded no excess above the background. The left plot in Figure 3 shows the resulting upper limits together with the calculated total neutrino flux. The properly scaled limit from the analysis of 416 bursts with the AMANDA-II detector [16] is also shown. Though only half its final size and using about a factor 4 fewer bursts, IceCube is already more sensitive than AMANDA-II and starts to set limits below the model predictions for prompt neutrino emission.

The right plot in Fig. 3 shows the current best limits on the neutrino flux from the precursor phase. The dashed thick line results from an analysis of data from 41 bursts

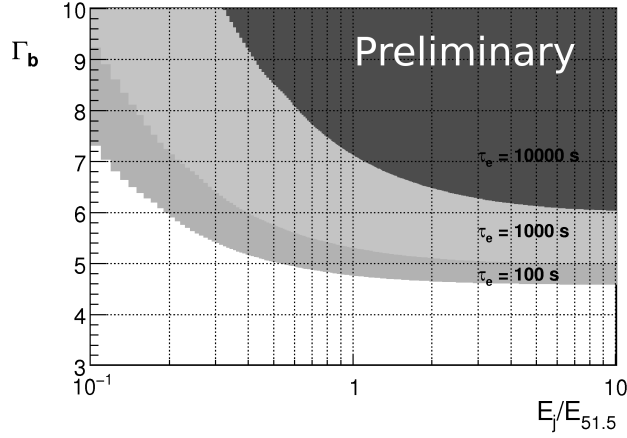


FIGURE 4. 90% CL upper limits in the Γ_b (bulk Lorentz factor of the jet) and $E_j/E_{51.5}$ (jet energy divided by $10^{51.5}$ erg) plane for three different search windows with width from 100 s to 10 000 s. Derived from the non-observation of neutrinos from SN 2008D under the assumption that its hypothesized jet was pointing towards Earth.

taken with IceCube in a 22-string configuration [17]. The thin dash-dotted line is the limit from a rolling search in the cascade channel with the AMANDA-II detector [18]. Though less sensitive than the IceCube analysis the latter is currently the best limit on neutrino fluxes from GRBs not detected in gamma rays. The limit excludes the case where all type II supernovae (SNe) exhibit choked jets (light dotted line).

An alternative approach to the detection of neutrinos from core-collapse SNe will be discussed in the next section.

Neutrinos from Core-Collapse Supernovae

Optical telescopes detect several hundred core-collapse SNe per year. The SN light curves rise during the first few days after which a slow decay over typically several tenths of days starts. The usual precision of the measurement allows the determination of the actual time of explosion to about one day [19], much larger than the expected neutrino emission time. This results in a large background when searching for associated neutrino emission and hence a decreased sensitivity.

In January 2008, the X-ray telescope aboard the Swift satellite was conducting a routine observation of NGC 2770 when it recorded a bright X-ray flash [20] that was later associated with SN 2008D, a core-collapse SNe of type Ib. The X-ray flash was interpreted as the signature of the shock break out. It provides the most precise information on the time of the SN explosion to date and hence allows for small neutrino search windows. Based on the model in [21] which predicts neutrino emission aligned with hypothesized jets, the data was analyzed using three search windows with durations between 100 s and 10 000 s. No event was observed in any of the three search windows and upper limits in the Γ_b - E_j parameter plane were determined (see Fig. 4).

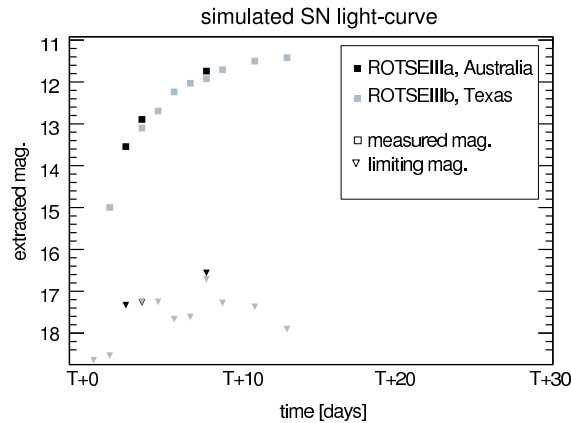


FIGURE 5. Results of the extraction of a simulated SN light curve which was injected into real background images taken with two of the ROTSE telescopes. The squares represent the measured magnitude. The limiting magnitudes are displayed as triangles.

The Optical Follow-Up Program

Often data from other detectors are used to guide analyses of IceCube data. On the other hand, a coincidence of several neutrinos from a given direction within a short time window is itself an interesting target for observations with optical telescopes. Possible scenarios are a rising SN light curve over several days or the decreasing intensity of a GRB afterglow.

This so-called *optical follow-up* program of IceCube [22] searches for two or more neutrinos within a angular window of 4° which occur within 100 s. In case of a signal, a trigger is sent with less than 5 minutes delay (in 2009, before an upgrade to the processing system, the latency was a few hours) to robotic telescopes which perform a follow-up program during the following 14 nights. Currently, the program includes the four telescopes of the ROTSE network which have a large field of view of $1.85^\circ \times 1.85^\circ$ comparable to the angular resolution of IceCube and an almost 24 hour night-sky coverage. The images taken are automatically processed and variable sources are extracted. The results of a simulation using real background data and injected SN light curves is shown in Fig. 5. The rising part of the SN light curve is clearly visible. The system is successfully running since end of 2008 and data analysis is currently underway.

FUTURE PERSPECTIVES WITH ICECUBE

Future IceCube analyses will continue to span a wide range of scenarios from the individual analysis of exceptionally bright bursts over the stacked analysis of a large number of bursts detected by satellites to rolling window searches. For triggered searches, a good and high sensitivity coverage of the sky with gamma-ray satellites is essential. The Swift and Fermi satellites will operate at least until 2014 and 2013, respectively, where a 5 year extension for Fermi is likely. Future satellites like SVOM (start planned in 2012), UFFO

(start planned in 2015) and EXIST (possible start in 2017) will complement the existing ones and will provide a good coverage at least until 2020.

The fact that GRBs are still not very well understood requires a double-track approach. Model-specific analyses yield a high sensitivity as they are optimized for the corresponding neutrino spectra. On the other hand, in order not to miss any unknown mechanism of neutrino production more generalized but less sensitive searches that cover a large time window around GRBs are being performed and remain mandatory.

The sensitivity of the IceCube detector is still increasing significantly during the next years. Its operation is foreseen for at least 10 years. Given the fact that already with only half of its strings installed and one year of observation time it starts to set limits below flux predictions, the chances for neutrino detection from GRBs in the upcoming years are good. With a sensitivity about 10 times larger than needed to detect the Waxman-Bahcall GRB flux, generic models that assume GRBs as the major sources of ultra-high energy cosmic rays will be tested.

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